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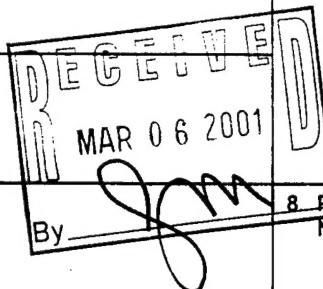
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Dr. A. Chattopadhyay



7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Arizona Board of Regents
Arizona State University, Office of Research and Creative Activities
P.O. Box 871603
Tempe, AZ 85287-1603

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13. ABSTRACT (Maximum 200 words)

The vibratory load reduction at rotor hub using self-sensing piezoelectric material and closed loop control is investigated. A composite box beam theory is developed to model the primary load carrying structure in the rotor blade. In this theory, a higher order displacement field is used to model the individual walls of the composite box beam with surface bonded piezoelectric actuators. Based on these techniques, an integrated rotor vibratory load analysis technique is developed by coupling an unsteady aerodynamic model with the rotor blade dynamic model. A pole placement technique is used to design the control system for vibratory load reduction. Significant reductions are observed in the modal responses of the rotor with closed loop control. Next, the use of segmented constrained layer (SCL) damping treatment is investigated for improving helicopter aeromechanical and isolated rotor stability. A new laminate theory based on a hybrid displacement field is developed and is used to model the composite box beam with distributed SCLs. The rotor blade load-carrying member is modeled using a composite box beam. Ground and air resonance analysis models are implemented and the effect of both passive and active control in improving coupled rotor-body stability is investigated. In the passive study, a hybrid optimization algorithm is used to study the optimal placement of the SCLs along with composite tailoring. Significant improvements are observed in inplane modal damping. A control system is designed to effectively address the time-variant system and is shown to further improve aeromechanical stability of a hingeless rotor.

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**MODELING AND ANALYSIS OF COMPOSITES USING SMART
MATERIALS AND OPTIMIZATION TECHNIQUES**

FINAL PROGRESS REPORT

February 6, 2001

Aditi Chattopadhyay – Principal Investigator

Qiang Liu – Graduate Research Associate

Rajan Beri – Graduate Research Assistant

Haozhong Gu – Post Doctoral Fellow

Changho Nam - Faculty Associate

Jong-Sun Kim – Faculty Associate

Department of Mechanical and Aerospace Engineering

Arizona State University

Tempe, AZ 85287-6106

U.S. ARMY RESEARCH OFFICE

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Modeling and Analysis of Composites using Smart Materials and Optimization Techniques

Aditi Chattopadhyay - Principal Investigator

Objectives

Task 1: Investigate vibration control of helicopter rotor blades using self-sensing piezoelectric actuators. Develop a new composite rotating box beam model with embedded piezoelectric (PZT) actuators to represent the principal load-carrying member in rotor blade. The structural analysis will be performed using a refined higher order displacement field that captures through-the-thickness transverse shear stresses. A comprehensive aerodynamic analysis procedure will be implemented for air loads calculation.

Task 2: Investigate rotor/fuselage coupled stability using passive segmented constrained layer damping treatment. Develop a new hybrid laminate theory to accurately capture the varying material characteristics and transverse shear stresses in the piezoelectric, viscoelastic and composite layers. Extend the new theory to model composite box beam with surface bonded segmented constrained layer (SCL) actuators. Perform parametric studies to investigate the impact of number and placement of the SCLs on aeromechanical stability. Utilize a hybrid optimization technique to investigate the optimal use of SCLs.

Task 3: Develop active control algorithm for the time-invariant system to increase damping of coupled helicopter rotor/body system in the presence of SCLs.

Task 1 Vibration Control

(Postdoctoral Fellow -Haozhong Gu, Graduate Research Associate – Qiang Liu, Faculty Associate –Changho Nam)

Approach: A composite box beam of arbitrary wall thickness is used to model the principal load-carrying element in the rotor blade. The higher order theory, which is based on a refined displacement field, is used to model its mechanical behavior. In this theory, both inplane and out-of-plane warping is included automatically. The developed model satisfies the stress free boundary conditions at the inner and outer surfaces of the beam. Continuities in displacements are also ensured at the interface between the composite laminate and the surface bonded PZT actuators.

The finite-state induced inflow model is used to calculate the dynamic rotor loads. An integrated rotor vibratory load analysis procedure is developed for analysis of rotor dynamic hub loads, which couples the unsteady aerodynamic model with rotor blade dynamic model based on the smart composite box beam theory. The unsteady aerodynamic forces are transformed into time domain by introducing the aerodynamic states. The finite element method (FEM) is employed to implement the refined higher order theory. A total of seven structural modes are used in the aeroelastic analysis. First, the rotor response and dynamic rotor hub loads are analyzed without closed loop control. Next, a linear quadratic regulator (LQR) theory is used for aerodynamic load control. A control system is designed for vibratory load reduction as well as for aeroelastic stability control. The nonlinear aerodynamic model is linearized for linear control system design. A pole placement technique is used to design the control system for vibratory load reduction. Parametric studies are performed with different number of PZT actuators and locations along the blade span. Significant improvements are observed in the modal response of the rotor using closed loop control.

Accomplishment: The integrated rotor loads analysis approach allows calculation of both rotor hub loads and rotor aeroelastic stability in the presence of selfsensing piezoelectric actuators. The results of the parametric study shows that significant reduction in rotor dynamic hub loads is possible with closed loop control. However, the placements of the PZTs are not intuitively obvious and are governed by several factors including inplane and bending-twist coupling. The procedure can be integrated within a formal optimization loop to study design trade-off.

Task 2: Aeromechanical stability (Graduate Research Associate – Qiang Liu)

The use of segmented constrained damping layer (SCL) treatment and composite tailoring for improved rotor aeromechanical stability is investigated using formal optimization technique. A

hybrid displacement theory is employed to develop the structural equations of motion. A classical ground resonance model and an air resonance model are used to investigate the coupled rotor-body stability. The Pitt-Peters dynamic inflow model is used in the air resonance analysis under hover condition. A hybrid optimization algorithm, which effectively incorporates continuous and discrete design variables using both gradient-based and discrete search strategies, is used for the design of the smart rotor blade with segmented SCLs for improved passive damping. Parameters such as ply orientations and SCL placement are selected as discrete design variables. Constraints are imposed on the fundamental lead-lag and flap frequencies to ensure that the dynamic characteristics of the hingeless rotor are maintained. It is shown that optimum blade design yields significant increase in rotor lead-lag regressive modal damping compared to the initial system.

Accomplishment: The developed procedure is suitable for investigating ground and air resonance stability of helicopters with composite rotor blade sections. The hybrid displacement field approach is efficient and accurate in capturing the material characteristics at various levels as well as the transverse shear stresses. The results show that segmented constrained layer damping treatment can be very effective in passive augmentation of in plane damping.

Task 4: Control System Design for SCL Damping Treatment (Faculty Associate - Jong-Sun Kim, Graduate Research Associate – Qiang Liu and Graduate Research Assistant – Raj Beri)

Approach: A control system is designed to investigate further improvement in coupled rotor-body stability using segmented constrained layer damping treatment. The time-variant rotary wing system is converted to a time-invariant system, by introducing a transformation matrix. A LQG controller for the transformed system is then designed based on the available measurement output. The control performance is compared with the results of the open loop and the passive control systems.

Accomplishment: The developed control algorithm is suitable for improving ground and air resonance stability. Numerical study shows that the control system with surface bonded SCLs significantly increases rotor lead-lag regressive modal damping in the coupled rotor-body system.

Publications:

1. Liu, Q. and Chattopadhyay A., "Improved Helicopter Aeromechanical Stability Analysis Using Segmented Constrained Layer Damping and Hybrid Optimization", *Journal of Intelligent Material Systems and Structures* (in press).
2. Chattopadhyay, A., Gu, H., Nam, C. and Beri, R., "Modeling Segmented Active Constrained Layer Damping Using Hybrid Displacement Field", *AIAA Journal*, Vol. 0, 6, June 2001(in press).
3. R. Beri and Chattopadhyay, A., "Optimization of Smart Composite Plates with Segmented Active Constrained Layer Damping", AD-Vol. 63, 177 – 186, ASME International Mechanical Engineering Congress and Exposition, Orlando, FL, November 2000.
4. Chattopadhyay, A., Liu, Q. and Gu, H., "Vibration Reduction in Rotor Blades Using Active Composite Box Beam", *AIAA Journal*, Vol. 38, No. 4, April 2000.
5. Chattopadhyay, A., Kim, J.S and Liu, Q., "Aeromechanical stability analysis and control of smart composite rotor blades", Smart Structures and Materials 2000, 19-21 June, 2000, Madrid, Spain.
6. Liu, Q. and Chattopadhyay, A., "Improved helicopter aeromechanical stability analysis using segmented constrained layer damping and hybrid optimization", Smart Structures and Integrated Systems (ss02), Part of SPIE's 7th Annual International Symposium on Smart Structures and Materials, 5-9 March, 2000.
7. Beri, R., Chattopadhyay, A. and Nam, C., "Integrated Structures/Control Optimization of a Smart Composite Plate with Segmented Active Constrained Layer Damping", Paper No. SPIE 3985-80, *Proc.*, SPIE's 7th International Symposium on Smart Structures and Materials, Newport Beach, CA, March 2000.

8. Liu, Q., Chattopadhyay, A., Gu, H. and Zhou, X. "Use of Segmented Constrained Layer Damping Treatment for Improved Helicopter Aeromechanical Stability", *Journal of Smart Materials & Structures*, 9, 2000, pp.523-532.
9. Chattopadhyay, A., Gu, H. and Liu, Q., "Modeling of smart composite box beams with nonlinear induced strain", *COMPOSITES: Part B 30 (1999)*, pp.603-612.
10. Liu, Q., Chattopadhyay, A., Gu, H. and Zhou, X. "Effect of Active Constrained Layer Damping Treatment on Helicopter Aeromechanical Stability Analysis", *Proc., 55th Annual Forum of the American Helicopter Society*, Montreal, Canada, May 25-27, 1999.
11. Chattopadhyay, A., Liu, Q. and Nam, C., "Rotor Vibratory Response Analysis Using Smart Materials and Aeroelastic Control", *Proc., AIAA/ASME/ASCE/AHS/ASC Structural Dynamics, and Material Conference*, St. Louis, MO, 12-15, April, 1999.
12. Chattopadhyay, A., Liu, Q. and Gu, H., "Aeromechanical Modeling of Smart Composite Rotor Blade for Vibration Reduction", *Proc., 54th Annual Forum of the American Helicopter Society*, Washington D.C., May 29-31, 1998.

Participating Personnel:

<u>Name</u>	<u>Degree</u>	<u>Graduation Date</u>	<u>Employment Date</u>
Rajan Beri	MS	August 2000	1/15/99-8/15/00
Qiang Liu	Ph.D.	December, 2000	12/15/1996-12/15/00